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Design-to-Cost for Space Missions

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Design-To-Cost for Space Missions*

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Design-to-Cost (DTC) was originally a term used in Department of Defense (DoD) programs to denote a concern for the production cost of a system during the definition, design, and development phases of a program or project, This was appropriate because, in many DoD programs, production runs in the hundreds or thousands of end items were usually contemplated. The term later evolved into Design-to-Life-Cycle-Cost (DTC/LCC) when concern for operations and support was added. Operations and support costs, when viewed over the entire life of a weapon system, often comprised the majority of the life-cycle costs (LCC). Today, either term is a moniker for an approach to life-cycle cost management. Life-cycle cost management is the complete integration of life-cycle cost considerations into the systems engineering and design process--that is, LCC is treated as a system attribute and is managed accordingly. This is the way we use the term *DTC* in this paper.

The DoD directive on DTC dates back to the 1980s.1 It requires that "flyaway" or unit production cost goals and threshholds be established and presented for each major weapon system before final commitment to full-scale development. Establishment of additional DTC parameters for operations and support is suggested, but not mandatory. The purpose of this approach to DTC is to control LCC by requiring designers and acquisition managers to work within a minimum performance floor and maximum affordable cost ceiling. Once these goals and threshholds are established, managers are suppose to "strive" to meet them, and to report periodically on the current estimates for their system's DTC parameters?

NASA space missions typically involve only a very small number of end items, typically one or two. The argument for doing DTC in NASA missions, then, may not seem very compelling. However, as Wertz and Larson point out, "cost is a fundamental limitation to nearly all space missions."[3] Given the new realities of NASA post-Cold War budgets, future NASA missions face a budgetary environment in which lower cost projects are the norm and a program management environment in which cost overruns can jeopardize a project. By current guidelines, overruns on development and/or life-cycle costs by as little as

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● This work was supported by the JPL Project Design Center (PDC).

[1]Department of Defense Directive 4245.3, Design *to Cost,* April 6, 1983.

[2]The extent of compliance with the DoD DTC directive today is unknown, but a 1987 study found that of 35 DoD programs, about only two-thirds established flyaway or unit production cost goals and threshholds, and only ten percent had operations and support DTC parameters. None of these programs were space missions. See Department of Defense, *Report on the Survey of the DoD Application* of *Design-to-Cost Principles,* Inspector General Report No. 87-109, April 1987. While the DoD approach is well-intentioned, we feel that process by which such goals and threshholds are established could be improved.

[3]Larson, Wiley, and James Wertz, (cd.), *Space Mission Analysis and Design,* 2nd Edition, p. 1.

15 percent may result in mission cancellation.' With hard cost constraints like that, DTC is a necessity. Even if cost is not a hard constraint, OTC provides greater cost-effectiveness and economic efficiency. In a commercial space venture, this translates into greater profit, and perhaps market share.

In our view, DTC is not just an acquisition management technique or just a technical process within systems engineering. Managing cost as a system-level parameter requires both the commitment of project management as well as the technical expertise provided by a variety of mission and system engineers and cost estimators. Further, a space mission must have a strong DTC focus from its early conceptual studies in order for DTC to work. This is because so much--70 *percent by some estimates--of* a mission's life-cycle cost is determined during the conceptual studies and mission definition phases of a project.

NASA commitment to DTC is relatively new. The governing document for major system acquisition, NMI 7120.4/NHB 7120.5 (November 1993), states that projects must maintain the capability to estimate, assess, and control LCC throughout the project cycle. In Preliminary Analysis and Definition (Phases A and B, respectively), this capability focuses on the LCC effects of varying mission design and mission effectiveness parameters. Such high-level trade studies help identify whether a slight relaxation of performance requirements could result in a significantly cheaper system or whether a small increase in LCC resources could produce a significantly more effective one. Before a project k approved for Design and Development (Phases C and D, respectively), it must establish both development and life-cycle cost targets, These are known as the Development Cost Commitment (DCC) and the Project Cost Commitment (PCC), respectively. These commitments can be renegotiated, if for example, external conditions change.

During Phases C and D, the LCC capability focuses on assessing the LCC effects of refinements in the system design, operations concept, and/or associated downstream processes (such as fabrication, verification, operations and support, and disposal). For major changes in system design, operations concept, and/or associated downstream processes, LCC effects must be estimated and submitted as a part of any formal change control requests. Change requests are examined for consistency with the DCC and PCC. Should the final projected development and/or life-cycle cost exceed the cost commitments by more than 15 percent, the project is subject to a Cancellation Review.

In this paper, we describe our approach to implementing the NMI/NHB's DTC mandate at JPL. The implementation has been applied only to projects that are in the early conceptual studies phase (also known as pre-Phase A) or Preliminary Analysis (Phase A). These projects tend to be smaller-a few tens of millions to a few hundreds of millions of dollars-than some of the planetary projects JPL has undertaken in the past, and they are highly cost-constrained. The DTC approach could, however, be applied to both large and small projects, and to both crewed and robotic missions.

1.1 Design-to-Cost in Systems Engineering and Management

Design-to-cost is a way of implementing a project so that it yields maximum mission returns while keeping costs within a specified amount. For organizations that are accustomed to working in a highly cost-constrained environment, the systems engineering process is likely to have evolved in a way that naturally supports DTC; in other organizations, DTC requires a shift to a new approach to systems engineering. The difference is illustrated in Figure 1, which contrasts the requirements-driven systems engineering process with the cost-driven one. In the latter, mission *goals* and hard cost constraints replace hard mission capabilities requirements. The resulting mission implementation reflects capabilities scoped as needed to meet the cost constraints.

in a capabilities requirements-driven process, project-level requirements are allocated to the

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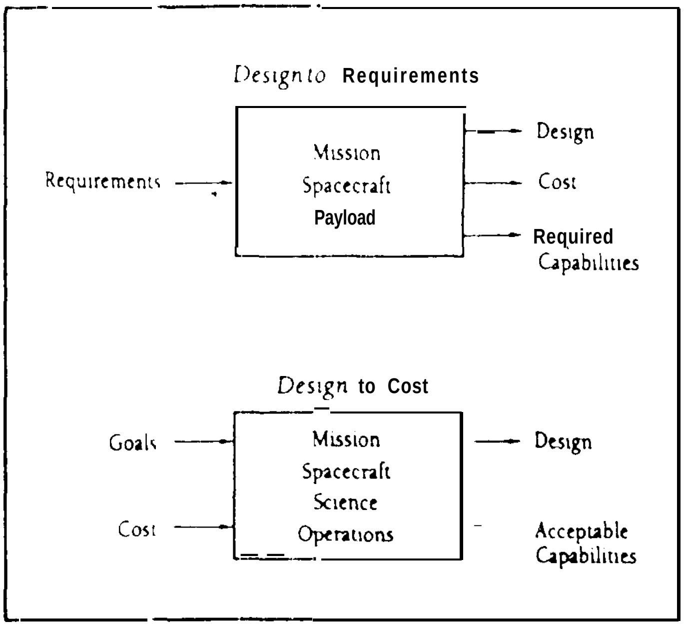
[4]NASA Headquarters, *Management of Major System Programs* **and Projects,NMI7120.4/NHB** 7120.5, November 1993.

various systems (i.e., spacecraft, mission operations, mission design and launch vehicle), and system-level requirements are allocated to various subsystems (i.e., power, attitude control, etc.) These allocated requirements are ultimately translated into a feasible mission implementation, which is then costed. (In the past, operations were typically costed separately, and only after the mission design and spacecraft design were well-understood.)

This approach has led to several problems: The subsystem design organizations often do not fully account for the cost burden their designs place on the project as a whole. This “interface” problem results in costs being thrown “over the fence. ” A particularly common example occurs when a particular spacecraft design offloads costs into the verification and/or operations phase of a project. Each subsystem design organization tends to optimize the performance of its own subsystem rather than optimize the performance of the project as a whole. Each may guard information about costs and technical margins in order to avoid risk in its own subsystem. Often there is a premature focus on a preferred technical design so there is little exploration of alternatives, and little room for descoping.



igure 1—Comparative Design Methodologies

Elements of a Design-to-Cost Process

In a cost-driven DTC process, the basic elements of good systems engineering are still present. For each project, these elements include:

- Flowdown of guidance in the form of mission and/or science goals, cost constraints (by year or phase, if necessary), risk and margin policies, and engineering and management plans.
- Concurrent engineering-that is, the simultaneous consideration of all downstream processes such as fabrication, verification, operations, and disposal.
- Rigorous, consistent evaluation of alternative mission implementations considering cost, schedule, performance, risk,
- Successive refinement of the mission implementation through architecture, preliminary design, detailed design, etc., iterating as needed in response to new ideas and trade studies. In this process, mission and/or science requirements “float” until the costs are understood well enough to meet cost constraints with high probability,
- Tracking of technical progress and DTC thresholds, in particular, through the project cycle to ensure that what is delivered is capable of performing a useful mission within the cost constraints.

Over the longer run, a DTC process also requires:

- Maintenance of design tools, models, engineering and cost data bases, etc.
- Continuing education of system engineers to use the design tools and models that support DTC, and in DTC techniques.

Design-to-Cost at JPL

JPL space missions have traditionally been requirements-driven, but future JPL missions are very likely to be cost-driven, smaller, and completed in less time than in the past. To accomplish this, JPL has moved toward the concepts of small integrated Product Development Teams (PDTs), concurrent engineering, and DTC. All three are facilitated by a new Project Design Center (PDC). The PDC enables project teams (i.e., PDTs) to include LCC as a direct part of each mission implementation decision. In the PDC environment, project teams concurrently conduct the DTC iterations throughout the project cycle. The PDC is designed to speed up the decisionmaking process: If a proposed mission implementation results in an estimated project cost exceeding the cost constraint(s), PDC capabilities can help to significantly reduce the cycle time for iterations among members of the project team needed to resolve the issues. These capabilities include multiple computer workstations supporting and linking cost databases, project archives, models specific to each technical design discipline, and a *project-level DTC model.* The PDC facility can be computer- and video-linked to similar facilities across the U.S.

Our DTC approach involves much greater use of trade studies conducted via the project-level DTC model. The *raison d'être* of the DTC model is to assist in the key design decisions so that they can be made under conditions in which the project team is better informed about the relationship of technical performance and design attributes to cost. The trade studies are far more comprehensive than in the past, because the DTC model takes account of the interactions across spacecraft subsystems and between the spacecraft and the other parts of the project. There is more visibility and consistency to the assumptions being made and to estimates of project-level technical and LCC implications. Use of computers means there is faster turnaround when "what if' questions are posed, and less back-of-the-envelope calculation. Documenting and archiving of trade studies, which provides traceability of decisions, occurs naturally when the DTC model is used. DTC becomes a continual process, not a once or twice a year exercise.

DTC is also related to a project's risk *management* activities in at least three ways worth mentioning here. First, grass roots cost estimation and modeling (done as a part of DTC) can be performed stochastically. A Monte Carlo simulation of the total cost results in a cumulative probability distribution (cdf) that can be used to calculate project cost reserves as a function of the project's desired level of confidence that actual costs will not exceed the cost cap. Second, the DTC model can be used by the project team to develop descoping options. This is best done fairly early in the project cycle when various mission architectures are being evaluated. The DTC model provides an estimate of how much LCC can be reduced by varying technical performance and design attributes. These descoping options should be archived so that they can be rapidly brought up should it prove necessary. Third, the DTC model also provides a means of automatically calculating a number of high-level *Technical Performance Measures* (TPMs) such as estimated mission effectiveness metrics and mass and power margins. In cost-constrained projects, estimated LCC (and perhaps its components) should be tracked so that they can be compared to their threshhold values, For all practical purposes, these cost metrics can be treated as TPMs as well.

Impediments to Design-to-Cost

Failure modes in doing DTC on a project are easily found. One can be found in the political process for obtaining a new project start. When management is primarily focused on selling a project, DTC may even be viewed as a threat. The DTC requirement, expressed in NMI 7120.4/NHB 7120.5, that major projects be able to estimate and control LCC throughout the project cycle means that LCC information is available; for projects whose LCC is much larger than the development cost alone, such information may be used in the political arena by those who question the affordability of the project.

Another impediment to DTC is technical. When DTC techniques, tools, and models are either not very well understood by project teams, or not coherently implemented, DTC efforts will be ineffective. Our experience suggests that just having the DTC tools (e g., cost models, data bases, etc.) in place is not sufficient. The lack of training and experience in what to do and how to do it means that DTC tools will go unused.

A third impediment to DTC is organizational. DTC is effective only when project teams become convinced that it is part of their job, not a separate exercise. Management at all levels must communicate that DTC practices are imperative. When communication across technical disciplines is difficult, or fails to be open or timely, DTC has a low probability of success. The same can be said for communication across project phases, when the makeup of project teams may change. Lastly, there may arise a psychological impediment in some who prefer engineering judgment and distrust quantitative **decisionmaking.**

1.2 Some Basic Concepts

At this point, we introduce some basic concepts to help provide a foundation for the technical portion of our approach to DTC; some readers may recognize these as familiar concepts from cost-effectiveness and systems analysis, and may wish to proceed directly to Section 1.3. By the nature of our approach, some of these basic concepts are abstract. Their application to an actual space mission, however, is not abstract, but requires a quantitative understanding of the underlying physical, engineering, and cost relationships for that mission.

We view the DTC problem as one of choosing a set (from among perhaps many such sets) of technical performance and design attributes that represents a wholly feasible alternate means of accomplishing the system's intended mission within a particular cost and schedule. For a particular mission, these technical performance and design attributes describe the relevant ***design space.*** We intend for the concept of a design space to include all things that describe a full mission implementation-mission design, system architecture/design, operations concept, etc. With a given state of technology, only a subset of the design space points (i.e., quantitative values for these attributes) are feasible. For example, only so much power output can be obtained from a given solar array area with currently available designs.

Each point in the design space maps into a *measure (or measures) of effectiveness.* The measure of effectiveness expresses quantitatively the degree to which the system's purpose (objectives) is achieved. For example, launch vehicle effectiveness depends on the probability of successfully injecting a payload onto a usable trajectory. Some associated technical performance attributes include the mass that can be put into a specified nominal orbit, the trade between injected mass and launch velocity, and launch availability.

Simultaneously, each point in design space maps into a quantitative measure of cost. It is also possible then to think of each point in design space as a point in the tradeoff space between effectiveness and cost. A graph plotting the *maximum* achievable effectiveness of designs currently feasible as a function of cost would in general yield a curved line like the one shown in Figure 2. In the figure, all the dimensions of effectiveness are represented by the ordinate and all dimensions of cost by the abscissa. The curved line represents the envelope of currently available technology in terms of cost-effectiveness. The feasible region contains the curve and the area below it.[5]

From this perspective, DTC becomes a matter of selecting the alternative that solves a constrained optimization problem. Such a problem can be formally stated as:

$$\begin{aligned} \max_{\{x\}} \quad & E(x_1, x_2, \ldots, x_n) \\ \text{subject to:} \quad & C(x_1, x_2, \ldots, x_n) \leq C \\ \text{and} \quad & x_1, x_2, \ldots, x_n \text{ feasible.} \end{aligned} \tag{1}$$

where $E(x_1, x_2, \ldots, x_n)$ is the function describing the effectiveness of the system design with technical performance and design attributes $x_1, x_2, \ldots, x_n$, and $C(x_1, x_2, \ldots, x_n)$ is the function describing its cost. C

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[5] Uncertainty complicates this simple picture because exactly what cost-effectiveness outcome will be realized by a particular design cannot be known in advance with certainty. For example, even the most robust design has some chance of a randomly occurring failure. The projected cost and effectiveness of a design are better described by a joint probability distribution than a point. The curved line in Figure 2 can be be thought of as representing the envelope at some fixed confidence level. For further discussion, see *NASA Systems Engineering Handbook (Draft),* September 1992, pp. 4-S.

is the fixed cost that cannot be exceeded. Equation (1) states that we seek to maximize effectiveness subject to a cost constraint. The first-order conditions for a solution to Equation (1) have a intuitive appeal; when all the functions are well-behaved, the *marginal effectiveness* of a change in any x_i is proportional to *its marginal cost* at the optimal values.

In real space missions, the functions in Equation (1) are such that it is impractical (or impossible) to write them down in closed form, so it is perhaps best to think of them as just the reduced form. Our examples from actual JPL flight projects in Section 1.4 will demonstrate how involved the relationships can be. We wish to emphasize, however, exactly what role Equation (1) plays in OTC. We are definitely ***not*** saying that OTC is a mathematical problem that can be mechanistically solved with sufficient computing power. The reason we believe this is so is that the ***feasible*** *region is only uncovered through the creativity of the project team engineers who synthesis* ***alternative*** *design* ***solutions relevant*** *to that* ***particular*** *mission.* We are saying that this view of DTC allows those creative individuals on a project team to conduct a focused search through many alternative solutions that they believe feasible in order to find more highly valued ones. This search is, in fact, carried out (by performing trades) using the DTC model that is built for this purpose early in the OTC process.

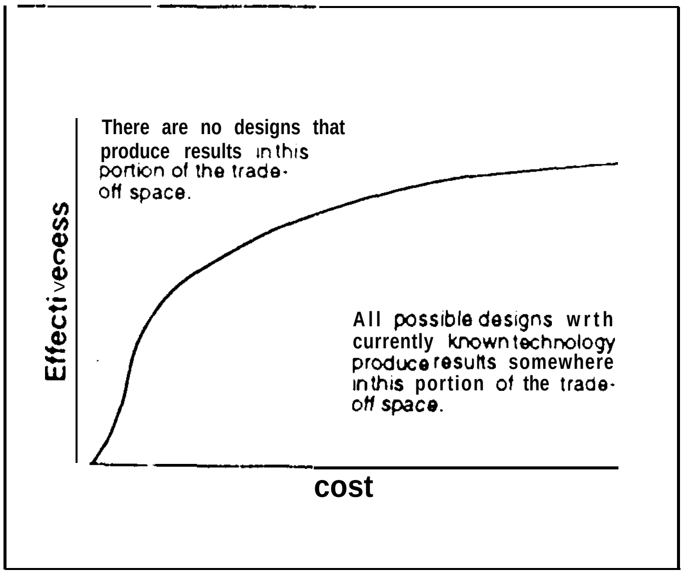

Figure **2—Cost-Effectiveness** Tradeoff Surface

Another basic concept that we use is life-cycle cost (LCC). LCC is the most comprehensive measure of the cost of a system. Informally speaking, a system's LCC is the total cost of its acquisition, ownership and disposal over its entire lifespan. LCC should be estimated and used (in Equation 1) in the evaluation of system alternatives during trade studies[6]. Two views of LCC are shown in Figure 3. The two views basically reflect institutional and mission differences rather than any substantive ones. The important point is that in LCC, operations costs (and disposal costs) are being treated concurrently with acquisition costs. Trades between the two should receive attention in OTC.

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[6]Technically, the cost function in Equation (1) should be the Present Value (PV) or Present Discounted Value (PDV) of life-cycle cost. See Wiley Larson and James Wertz, (ad.), Space *Mission* ***Analysis*** *and Design,* 2nd Edition, p. 722 for deflations In the DTC models described in Sections 1.3 and 1.4, we allow the model user to set the discount rate The higher this rate, the lower operations costs are "weighted" relative to development costs.

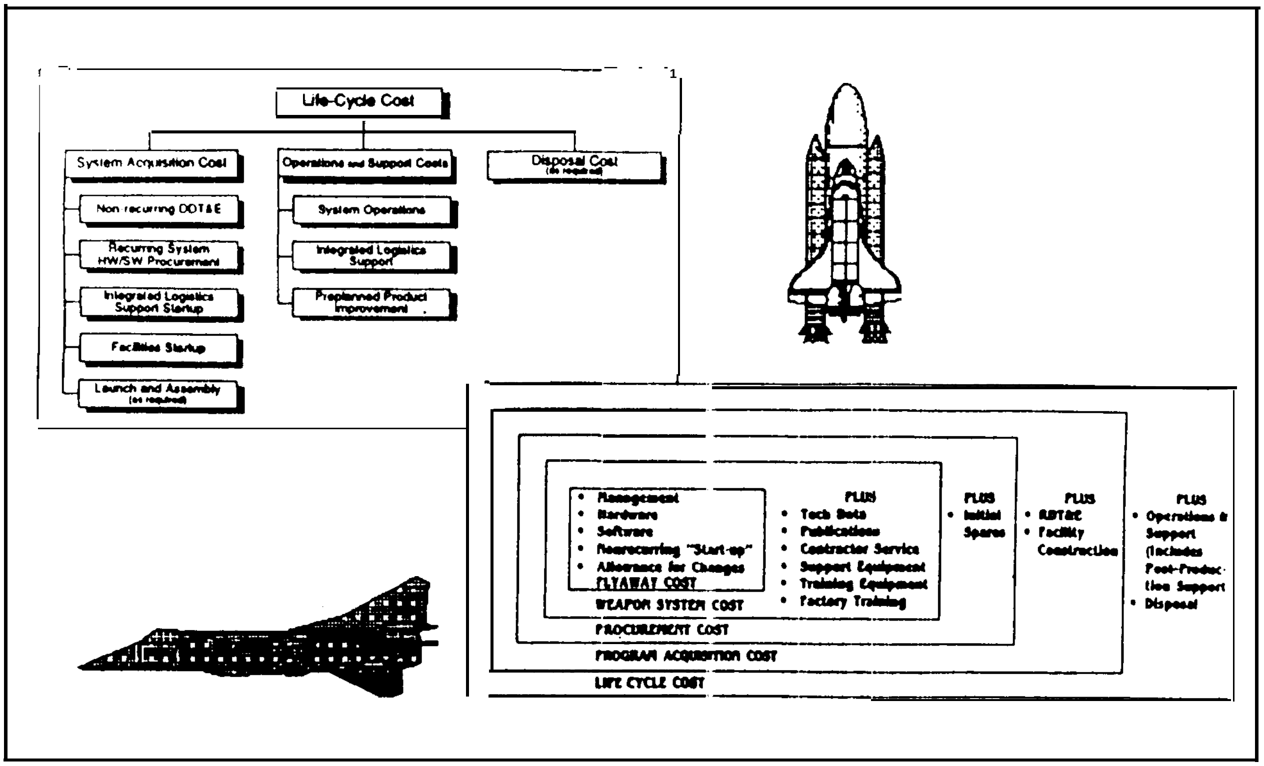

Figure 3-NASA (Top) and DoD (Below) Views of Life-Cycle Cost

1.3 Building the Design-to-Cost Model

The idea of linking technical design tools and models together is not new; the exchange of model results by engineers working in the same technical discipline is fairly common. The DTC model's strength is in the ability to link dissimilar technical disciplines through the effects on mission effectiveness and LCC. This section describes what we have done to implement the technical portions of the DTC process. Primarily, this involves building and verifying the DTC model, and using it to evaluate alternative mission implementations. In early conceptual studies and mission/system definition studies, there are a number of typical questions and/or issues that the project team must address. Some examples include:

- What are the "tall poles" driving the design and/or mission costs?
- What is the best balance of subsystem technical performance levels? (i.e., optimal sizes?)
- What potential payoffs do various "new" technologies offer?
- What trades of spacecraft capabilities/costs against mission operations capabilities/costs make sense?
- How much margin of finite resource x can be gained by lowering the margin of finite resource y?
- What is the project's best descoping options?

Addressing these kinds of issues is typically done in trade studies. These trade studies play a important role in determining technical performance and design requirements for the various systems and subsystems that make up the project. The ability to address the above issues in a systematic, quantitative, and rigorous manner requires a variety of models and tools. These include cost models, subsystem performance models, system-level effectiveness models, reliability models, and decision analysis tools. When these are integrated *in a particular way*, the result is a DTC model. Our approach to building a DTC model focuses on the top-level metrics of interest to the project such as life-cycle cost and mission effectiveness. We describe a space mission by a set of interrelated equations that leads to the calculation of these and other important (intermediate) technical performance and design variables. These equations represent a description of the space mission in cost-schedule-performance design space. When certain variables are treated stochastically, we are able to represent risk as well.

In our current DTC models for JPL projects, we use EXCEL 5.0, though our approach to DTC is not tied to that particular software package. The capabilities of commercial spreadsheets are now sufficient to handle the model sizes and complexities we are developing and using. Naturally, some software problems occur from time to time, but the advantages of using commercial spreadsheet programs in cost, portability, and extensibility are substantial, Another advantage is that tools are becoming available that allow us to link our spreadsheets with Unix programs that run on workstations. Two such programs include a mission design/trajectory analysis program and a CAD program for solid modeling of the spacecraft. Change a parameter in one of these programs, the spreadsheets calculate the "ripple" effects on the other subsystems and on the top-level metrics.

Our role as DTC engineers is actually in integrating the models and data that the cognizant system and subsystem design engineers already possess in one form or another. Our efforts do not duplicate what the system and subsystem design engineers do. Instead, we hold one-on-one meeting with each cognizant system and subsystem design engineer during which we acquire the mathematical equations for that system or subsystem. *All of the information for the DTC model comes from the project team, and as a* result, *the* project *team owns (and eventually uses) the OTC modal.*

The construction of the DTC spreadsheet model does not happen all at once in a "big bang," The scope and detail of these equations depends on the project's phase. During early conceptual studies, we focus on the issues the project team feels is driving the design solution. For example, in the Space Infrared Telescope Facility (SIRTF) project, the two key design challenges were attaining a telescope life of at least 2.5 years while fitting it within the fairing dimensions of the Delta II launch vehicle. A rigorous thermal analysis of various physical configurations was essential. The project team had three thermal models to choose from, and selected the one recommended by the cognizant thermal subsystem engineer. The DTC model was built around this set of equations.

The DTC model is first filled with equations and parameter values describing the project team's baseline mission implementation. For projects that are in the conceptual studies phase, this baseline may have only the barest description such as a target body, launch vehicle, launch date and feasible mission trajectory, and a spacecraft mass bogey. At this point, the equations in the **DTC** model might describe how the **trajectory** vanes with changes in spacecraft mass, how acquisition costs change with that mass, and how operations costs change with the **trajectory.** The model is not very useful at this point because, while we might have a relationship between **LCC** and mass, we do not know how much spacecraft mass is truly needed in order to **deliver** the payload of instruments and return the data collected. In order to gain usefulness (as well as confidence in the cost and technical performance estimates), the model needs to calculate a mission effectiveness metric, and have more subsystem and project cost detail. This detail is generally required in order to perform trades both within the spacecraft and across the spacecraft and mission operations systems. The subsystem detail includes basic subsystem design information (mass, power consumption, hardware cost, and **reliability** estimates all tied to an equipment list) and technical performance calculations. These are then aggregated to the spacecraft level and tied to **top-level** metrics such as **mission** effectiveness. Project cost detail-including full acquisition cost and **MO&DA cost--is** estimated and presented in a **top-level** project Work Breakdown Structure **(WBS).**

Mission effectiveness can be represented in several ways in the DIC model. For the **SIRTF** project, one measure chosen by the project team was the expected lifetime of the telescope, This metric is primarily a function of the size of the LHe dewar that cools the sensors, and the reliability of the spacecraft bus and telescope. Another approach to a mission effectiveness metric is to calculate the probability of getting at least x **gigabits** of returned science data. On missions to the outer planets, this metric is highly **reliability-dependent** and is significantly affected by whether the spacecraft has single-or **dual-string** subsystems. These decisions, in turn, affect mass, volume, **complexity,** and cost.

We next tie the subsystem technical performance equations to each other and to the cost equations. For most of the technical performance variables, **this** is fairly **straightforward.** The relationships among antenna size, radiated power and data return rates are established, for example, through the standard link budget. Naming these technical performance variables in EXCEL and using the names in the equations *insures* that changes are correctly propagated throughout the spreadsheets. Verifying the model is also more easily accomplished.

Tying in costs presents **a special** challenge. Spacecraft acquisition cost ***must*** be represented by equations that reflect its relationship to the subsystem technical performance and design attributes. The equations must be structured so that the correct ***cost gradients*--how** the cost changes when the performance attributes are changed-are applied. If appropriate Cost Estimating *Relationships* **(CERs)** are available, then these should certainly be used.' More often at JPL, we construct the appropriate CER for each subsystem using its grass roots cost estimate and what we call the *method of standard increments.* First, for each subsystem, we separate the acquisition grass roots cost estimate into frve categories:

- Management
- Design and development
- Flight hardware
- Integration and test **(I&T)**
- Software development.

For each technical performance attribute, we define a standard increment (say, for example a 10 percent increase), and we require that the cognizant subsystem design engineer then **re-estimate** the grass roots costs in each of the frve categories for this higher level of performance. **Although** this is an increase **in** the

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'Standard subsystem CERS can fail to be useful here for three reasons, First, they may not be performance-based. Second, they may be performance-based but not describe how costs change for all the ways the subsystem can increase performance. Third, statistical CERS are typically based on time series **(i.e.,** historical) data rather than on more relevant cross-section data, **As** a result, the calculated cost gradients reflect the "long run" rather than the current (i.e., "short run") trade of cost for performance.

amount of work the cognizant subsystem design engineer must perform, the added burden is generally accepted because of the perceived value of the completed DTC model. These cost gradients are used to form the relevant local acquisition cost equations. Cost spreading functions can be used to distribute these costs (by fiscal year) over the design and development period.

Mission operations and data analysis (MO&DA) costs must also be included in the DTC model. Equations representing MO&DA costs must also show cost gradients with respect to the mission design and operations concept parameters, and to the spacecraft technical performance and design attributes. Usually the MO&DA cost equations are highly specialized to the type of mission. We currently estimate MO&DA costs by fiscal year using a model developed at JPL (1992-94)8. This model, which is also in EXCEL, is completely integrated into the DTC model. (In 1995, we will upgrade this model to provide a more complete set of cost gradients.)

The DTC model at this point describes the baseline mission implementation, and is now ready to use in trade studies. If the baseline mission implementation exceeds the DCC and/or PCC, i.e., the programmatic cost targets, the baseline mission implementation is descoped sufficiently to meet them. A typical use scenario starts with a proposal to insert a new technology or change an item in the equipment list with a less powerful (and usually less expensive) substitute. Working at his/her own desk between regular project team meetings, the cognizant system or subsystem design engineer calls up the model on his/her computer and makes the necessary changes in parameters, equations, and databases for that subsystem. (Larger changes in the design may require that several engineers make changes in their respective parts of the model.) The system-level results, which may show an increase or decrease in LCC and/or, mission effectiveness, are reviewed at the project team's regular face-to-face meeting. An increase in costs that violates a cost constraint causes the project team either to reject the proposed change, or to initiates a search for a compensating change in another subsystem. (Note how the mission objectives and ' system/subsystem technical performance requirements float until the full cost implications are understood!) When the project team accepts a change, the new mission implementation becomes the baseline. The DTC process iterates this way as new ideas are suggested and tested using the model. Each decision is automatically archived by the project team by saving the DTC model used in that trade study,

In later phases of a project, the DTC issues move from fundamental ones to more detailed ones. For example, a project may wish to compare specific proposals for on-board processing of data to the ground processing alternative. The DTC model is modified to handle these more detailed questions as project definition and preliminary design proceed.

In summary, the DTC model should capture mission/system design knowledge and associated cost information; the model does not create designs, but it does process the underlying technical and cost relationships into new information about the top-level metrics of interest to the project. In particular, the model should be capable of producing reliable LCC projections for alternative mission implementations. Once a baseline mission implementation is established, the DTC model should be used to examine (through trade studies) the project's design space around the baseline. The DTC model should support the search for new mission implementations (i..e, points in the design space) that meet the cost constraint with confidence and are more highly valued in terms of cost-effectiveness. In the DTC process, when such an alternative mission implementation is found, it should become the new baseline, and the search resumed until further improvements are unwarranted.

The project team, not the DTC model, is ultimately responsible for successor failure of DTC. The model is only as good as the equations and data the project team provides to it. That depends on the quality of the project team personnel, their willingness to explore new alternatives, and openness in the search process.

'*See JPL Operations Cost Mock/for* ***Flight Projects*** in Wiley Larson and James Wertz, (ad.), Cost-Effective ***Space*** *Mission Operations,* forthcoming.

1.4 Two Examples of Design-to-Cost Models for Space Missions

This section presents two examples of DTC models, The first is for the now-cancelled Space Station *Freedom* (SSF). In building the SSF/DTC model, we acquired a great deal of valuable DTC experience. The model would be too large to present here in its entirety, but the application of our approach to a large program is outlined. The effort required to build the SSF/DTC model was considerable–several dozen workyears--much of which went to develop the custom software so that the model could be run on 386/486 PCs. The model was used to demonstrate potential savings of roughly a billion dollars (in present discounted value), so the return on investment would have been considerable had the recommendations been accepted and the program continued.

The second example deals with the Pluto Fast Flyby (PFF) project. The effort required to build the PFF/DTC model was only a few workmonths-a considerable reduction from the SSF/DTC model. The disproportional reduction can largely be attributed to the use of commercial spreadsheets to build the model and to the good fortune of having those who built the SSF/DTC model available to work on the PFF/DTC model.

Space Station Freedom

The first DTC model we developed was for Space Station *Freedom* (SSF) during the period 1985 though 1990." That model focused on the resources produced and consumed by each SSF subsystem. For example, the power subsystem produced power using large solar arrays, but required substantial logistics resources to provide the fuel for the propulsion subsystem to overcome the resulting drag. These interrelationships were modeled in detail along with the associated life-cycle costs. The earliest released version the SSF/DTC model dealt with 19 resources and their interrelationships; later versions modeled 80 resources.[10] The expansion of the model was due to the increasingly more detailed DTC questions that were being asked.

All versions of the model had the capability to automatically resize the subsystems that made up SSF so as to maintain a constant flow of net user services-that is, services available to SSF users after taking into account cross- and self-(parasitic) consumptions. Using the power subsystem example again, larger solar panels increased the net user power, but the cross-consumption of logistics resources also increased, which required an offsetting increase in logistics resources to maintain the same net to users. The costs associated with all these increases were then calculated by the model. It was then possible to compare the LCC of two alternative SSF designs with the *quantities of net user services held constant.* This provided an unambiguous discriminator of the two designs. The one with the lower LCC, properly discounted, was preferred.

The model could also be used to calculate the LCC of different quantities of net user services for the same configuration, and to calculate the LCC holding some of the 80 resources fixed. In the latter case, the net user services of those resources that were held fixed would be recalculated by the model. The extensive calculations were performed using custom software developed for the SSF program running on 386/486 PCs. A separately developed model, called *MESSOC*,[11] was used to calculate the operations costs and performance variables. Operations costs made up more than half of the LCC over SSF's 30-year useful life.

'The idea of developing and using a OTC model for space missions has been independently implemented by Rockwell's Space System Division and the Lockheed Space and Missiles Company for use *on* a classified program for the USAF Space and Missiles System Center.

[10] *System Design Tradeoff Model Version 13,* JPL D-5767/Rev. C, October 1990

[11] *Model for Estimating Space Station Operations Costs (MESSOC) Version 2.2 User Manual,* JPL D-5749/Rev. B, October 1990.

A Robotic Mission to Pluto

The Pluto Fast Flyby was conceived as a mission to send a pair of identical Plutonium-powered spacecraft to Pluto using a direct trajectory so as to arrive before the planet's atmosphere froze. (Pluto's orbit carries it inside that of Neptune's until 1999, and its atmosphere essentially collapses as it moves further from the Sun.) Each spacecraft was to be **capable a, capturing,** storing, and returning **1Gbit** of science data. The mission design was such that the two spacecraft would be launched on separate launch vehicles, arrive at Pluto six months apart, and each would image one-half of the planet. PFF was intended as a medium cost project.

Figure 4 shows the basic spreadsheets represented in the **PFF/DTC** model, but the illustration applies to **planetary** missions in general, The arrows indicate some of the data and calculations that are passed from one spreadsheet to another. The flight system is represented by a series of spreadsheets, generally one for each subsystem. Each spreadsheet contains equations and data to calculate the mass, power demands by flight mode, **DDT&E** and flight hardware/software costs, and reliability of the subsystem. Each spreadsheet also contains any governing equations needed to calculate subsystem performance. The telecommunications spreadsheet, for example, contains the link budget and passes tracking time results to the DSN spreadsheet. Mass and power by flight mode results are passed to separate accumulation spreadsheets, where, for example, the projected wet mass **is** calculated and passed to the mission design (MD) spreadsheet. The MD calculations are revised and key dates are passed to the **MO&DA** cost model spreadsheet. Mission operations costs are revised and passed to the LCC accumulation spreadsheet. The MD spreadsheet also contains the required ***delta-v*** for the mission. To calculate on-board propellant and wet mass, EXCEL must iterate through the propulsion, mass accumulation, and MD spreadsheets to obtain the solution.

In the **PFF/DTC** model, mission effectiveness is quantified by several (related) **risk-based** metrics. These are the probability of obtaining at least 1 **Gbit** of returned science data, the expected science data returned, and the *certainty equivalent* science data returned .12 These are **all** calculated using the techniques of decision trees, decision analysis, and reliability engineering. Tying in mission risk metrics makes it clear why there are no free lunches in space missions. **All** other factors held constant, using lower quality parts, or going single-string rather than dual-string (or single spacecraft rather than dual spacecraft), or extending the mission length, all exact **a** price in terms of these risk-based metrics. The **PFF/DTC** model calculates the amount to the extent the reliability equations (e.g., R(t) = $\exp(-\lambda t)$) and data are accurate.

In all of our DTC models, a single spreadsheet summarizes the **top-level** project metrics. This integrated summary spreadsheet presents the LCC (by Level 2 and 3 WBS elements), the flight system beginning of mission **(BOM)** power *and margins for critical flight modes, the* flight system dry, wet, and injected masses and *mass* ***margins***[13], and the three risk-based mission effectiveness metrics. The integrated summary also shows key programmatic parameters for the mission. The integrated summary is organized so that when trades are performed against the baseline mission implementation, the results for each of the project metrics can be compared item-by-item. A three-column **display is** used: one for the baseline mission implementation, one for the current alternative under consideration in **a trade study, and** the third for the differences. When a trade study is performed, the baseline numbers do not change. All trade results appear in the second column, and the deltas appear in the third; the baseline **numbers** change only when the alternative ***replaces*** (dethrones) the baseline,

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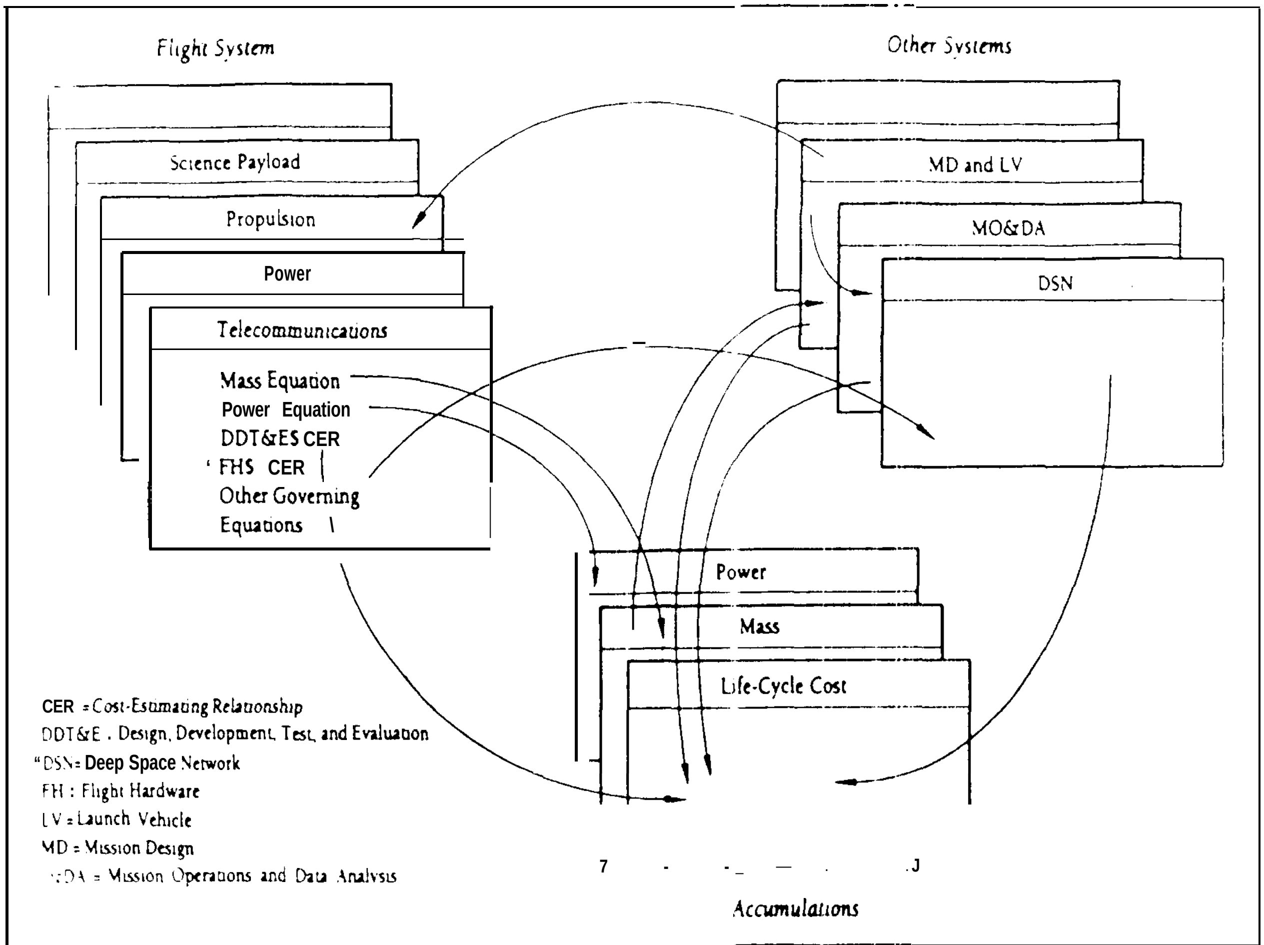
[12] *Certainty equivalent* here means the amount of science data **(say,** x **Gbits)** that leaves the **decisionmaker** (who could be the sponsor, project **scientist,** or project manager) indifferent between the choice of x with certainty and the uncertain amount he/she will actually receive from the mission.

[13] **PFF** doesn't track mass margins since mass is not a constraint for this mission, Instead, additional mass slows the flight system and results in longer cruise time to Pluto.



igure 4-Typical Space Mission Spreadsheets and Passed **Data**

Navigating through all the spreadsheets (approximately 35 in the **PFF/DTC** model) **is** made easier through a series of macro commands to EXCEL that are activated by clicking on the appropriate box in the tree structure shown as Figure 5. This graphic also **serves** as the DTC model's organizing structure. Clicking on the toplevel box marked ***Pluto*** *Project* opens the integrated summary spreadsheet, shown as Figure 6. The baseline mission implementation (and the current column as no alternative is being **evaluated** here) shows a two-spacecraft mission "using two Proton launch vehicles with the first launch date in January 2001. The PFF project team considered several trades. What would the implications of using a different launch vehicle (e.g., **a Delta 11)?** Should the **high-gain** antenna be larger or smaller? Would the use of a composite structure rather than aluminum payoff? Should the power subsystem output be increased by the addition of another RTG (Radioisotope Thermal Generator) Pu238 "brick"? We will illustrate the detail in **PFF/DTC** model using the last question. In the process, we will show three basic parts of the RTG subsystem spreadsheet: technical performance equations, equipment list with embedded mass equations, and cost equations. The RTG subsystem was one of the easier ones to model; the spreadsheets for the attitude and articulation control **(AAC)** subsystem, for example, are more difficult to develop fully.

Pu238 has **a** half-life of approximately 87 years. The Pu238 available for the PFF project was manufactured in July 1983. The thermal output of each brick, P(t), decays exponentially as a function of the time since the date of manufacture, t_m, according **to** the following equation:

$$P(t) = P(t_m)\, e^{-(\ln 2)(t - t_m)/86.4} \qquad (2)$$

The RTG itself degrades from a variety of environmental factors so that the available power, $P_{av}(t)$, declines as a function of the time since the launch date, t_d, in a manner predicted by the following equation:

$$P_{av}(t) = P_{av}(t_d)\, e^{-.0318\,(t - t_d) + .0009\,(t - t_d)^2} \qquad (3)$$

Together, Equations (2) and (3) give the available power for any date during the mission once the launch date is fixed. Mission design becomes a major factor in the determination of power margins since the later the launch date and the longer the cruise time to Pluto, the less power is available in all flight modes. Critical flight modes occurring near the end of the mission will feel this effect the most. Equation (4) shows the computation of the power margins for each flight mode, j.

$$\text{Power margin}_j = \min_{\{T_j\}} \left(P_{av}(t) - \sum_i P_{demand,\,j,\,i} \right) \qquad (4)$$

where T_j is the set of times $t > t_d$ such that the spacecraft is in mode j, and the summation of **power** demands is carried out over all flight subsystems including the science **payload. Figure** 7 shows the spreadsheet for the computation of power margins for each **flight** unit and critical flight mode.

Figure 8 shows the mass computation for the RTG subsystem based on its equipment list. When a Pu238 brick (i.e., the ***standard increment***) *is* added, the mass is automatically recomputed by equations that

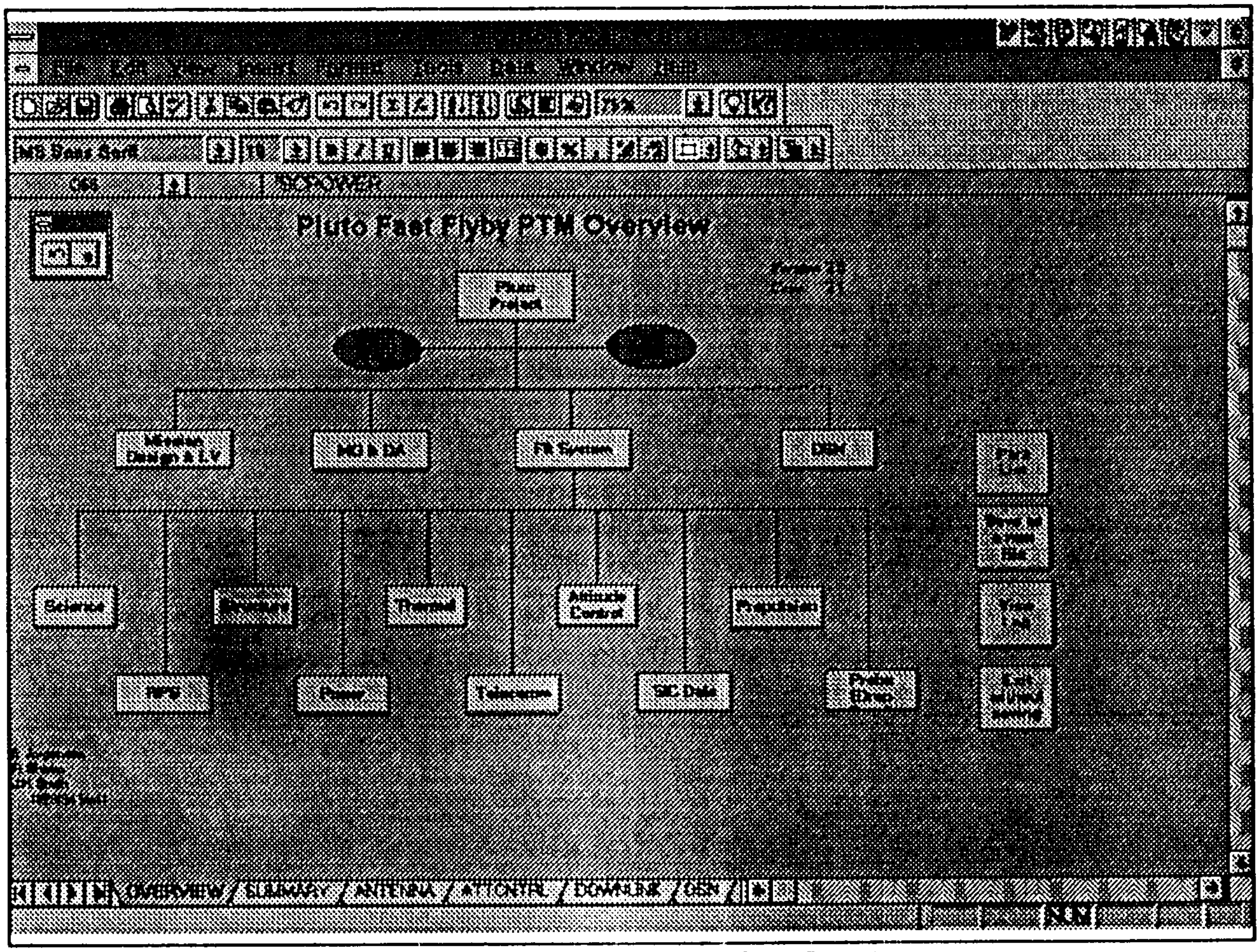


Figure 5—Overview of Pluto Fast Flyby DTC Model Spreadsheet Structure

Figure 6—Pluto Fast Flyby Integrated Summary

	JPL Project Design Center		
Pluto Fast Flyby PTM integrated Summary			
Project Name:	Pluto Fast Flyby		
Base Year:	$1993K		
Discount Rate (%):	0%		
	BASELINE	CURRENT	
Launch Vehicle:	Proton/DM/3-stage	Proton/DM/3-stage	
Launch Date:	1/28/01	1/28/01	
Number of Spacecraft:	2	2	
Number of Launch Vehicles:	2	2	
Project Management	[illegible]	[illegible]	[illegible]
S/C System	[illegible]	[illegible]	[illegible]
Payload System	[illegible]	[illegible]	[illegible]
RTG Development	[illegible]	[illegible]	[illegible]
MOS Development	[illegible]	[illegible]	[illegible]
Launch Adapter	[illegible]	[illegible]	[illegible]
Launch Vehicle	[illegible]	[illegible]	[illegible]
MO&DA	[illegible]	[illegible]	[illegible]
DSN	[illegible]	[illegible]	[illegible]
Total ($1993K)	[illegible]	[illegible]	[illegible]
Number of Modules	[illegible]	[illegible]	[illegible]
Beginning of Mission Poww (watts)	[illegible]	[illegible]	[illegible]
Power Margin (watts)			
Flight Unit 1			
Flight Unit 1 Mode 1 Power Margin	[illegible]	[illegible]	[illegible]
Flight Unit 1 Mode 2 Power Margin	[illegible]	[illegible]	[illegible]
Flight Unit 1 Mode 6 Power Margin	[illegible]	[illegible]	[illegible]
Flight Unit 1 Mode 7 Power Margin	[illegible]	[illegible]	[illegible]
Flight Untt 2			
Flight Unit 2 Mode 1 Power Margin	[illegible]	[illegible]	[illegible]
Flight Unit 2 Mode 2 Power Margin	[illegible]	[illegible]	[illegible]
Flight Unit 2 Mode 6 Power Margin	[illegible]	[illegible]	[illegible]
Flight Unit 2 Mode 7 Power Margin	[illegible]	[illegible]	[illegible]
Spacecraft Dry Mass	[illegible]	[illegible]	[illegible]
Spacecraft Wet Mass	[illegible]	[illegible]	[illegible]
Spacecraft Injected Mass	[illegible]	[illegible]	[illegible]
	Risk-Based Mission Success Summary		
	BASELINE	CURRENT	CURRENT - BASELINE
Prob(Data Volume >= 1.0 Gb)	0.%1	0.951	0.00
Expected Data Volume (Gb)	1.s66	1.558	0.00
Expected Utility (Data Volume)	1.175	1.175	0.00
Certainty Equivalent Data Volume (Gb)	1.357	1.357	0.00

Figure 3—Power Margins Computation

GOVERNING EQUATIONS			
BASELINE GPHS RTG POWER SOURCE DESCRIPTION			
Source: Green Book, Sectio	.0 Spacecraft, RTG Charts		
Name	alue	Units	Formula Text/Comment
Launch Vehicle =	otan/DMG-age	N/A	See MISSION.XLS for list of launch vehicles.
Launch_Date	1/28/01	mm/dd/yy	See MISSION.XLS for list of launch dates.
Fuel source =	ssini Old	N/A	See PU238.XLS for fuel decay rate.
Mfg_Date	7/1/83	mm/dd/yy	See PU238.XLS for fuel manufacture date.
No_Fuel_Modules	6	quantity	Enter integer quantity - calculate power margin given power demand for Modes 1,2,6,7.
Therm_Elect_Eff	0.07	dimensionless	Thermal-Electric conversion efficiency.
BOM_Therm	218.07	Watts	PU238.XLS!Ther_Watts_Start*EXP(PU238.XLS!Decay_Rate*(Launch_Date-PU238.XLS!Mfg_Date)/365.25)
BOM_Unit_Elect	15.26	Watts	Therm_Elect_Eff*BOM_Thermal
BOM_Total_Elect	91.56	Watts	No_Fuel_Modules*BOM_Unit_Elect
Power Demand Analysis			
Mode1_Total_Power	57.16	Watts	PWRMODE.XLS!Mode1_Total_Power
Mode2_Total_Power	67.66	Watts	PWRMODE.XLS!Mode2_Total_Power
Mode6_Total_Power	66.67	Watts	PWRMODE.XLS!Mode6_Total_Power
Mode7_Total_Power	66.16	Watts	PWRMODE.XLS!Mode7_Total_Power
Flight Unit 1			
FU1_Mode1_Date	12/1/06	mm/dd/yy	
FU1_Mode2_Date	12/1/06	mm/dd/yy	
FU1_Mode6_Date	12/11/06	mm/dd/yy	
FU1_Mode7_Date	1/22/09	mm/dd/yy	
Flight Unit 2			
FU2_Mode1_Date	5/22/06	mm/dd/yy	
FU2_Mode2_Date	5/22/06	mm/dd/yy	
FU2_Mode6_Date	6/1/06	mm/dd/yy	
FU2_Mode7_Date	7/13/06	mm/dd/yy	
Flight Unit 1			
FU1_Mode1_Avail_Power	75.40	Watts	No_Fuel_Modules*Therm_Elect_Eff*BOM_Thermal*EXP(C:\EXCEL\PLUTO\GPHSRTG.XLS!alpha*((FU1_Mode1_Date-B6)/365.25)+C:\EXCEL\PLUTO\GPHSRTG.XLS!beta*((FU1_Mode1_Date-B6)/365.25)^2)
FU1_Mode2_Avail_Power	75.40	Watts	No_Fuel_Modules*Therm_Elect_Eff*BOM_Thermal*EXP(C:\EXCEL\PLUTO\GPHSRTG.XLS!alpha*((FU1_Mode2_Date-b6)/365.25)+C:\EXCEL\PLUTO\GPHSRTG.XLS!beta*((FU1_Mode2_Date-b6)/365.25)^2)
FU1_Mode6_Avail_Power	75.36	Watts	No_Fuel_Modules*Therm_Elect_Eff*BOM_Thermal*EXP(C:\EXCEL\PLUTO\GPHSRTG.XLS!alpha*((FU1_Mode6_Date-B6)/365.25)+C:\EXCEL\PLUTO\GPHSRTG.XLS!beta*((FU1_Mode6_Date-B6)/365.25)^2)
FU1_Mode7_Avail_Power	75.21	Watts	No_Fuel_Modules*Therm_Elect_Eff*BOM_Thermal*EXP(C:\EXCEL\PLUTO\GPHSRTG.XLS!alpha*((FU1_Mode7_Date-B6)/365.25)+C:\EXCEL\PLUTO\GPHSRTG.XLS!beta*((FU1_Mode7_Date-B6)/365.25)^2)
Flight Unit 2			
FU2_Mode1_Avail_Power	76.13	Watts	No_Fuel_Modules*Therm_Elect_Eff*BOM_Thermal*EXP(C:\EXCEL\PLUTO\GPHSRTG.XLS!alpha*((FU2_Mode1_Date-b6)/365.25)+C:\EXCEL\PLUTO\GPHSRTG.XLS!beta*((FU2_Mode1_Date-bD6)/365.25)^2)
FU2_Mode2_Avail_Power	76.13	Watts	No_Fuel_Modules*Therm_Elect_Eff*BOM_Thermal*EXP(C:\EXCEL\PLUTO\GPHSRTG.XLS!alpha*((FU2_Mode2_Date-b6)/365.25)+C:\EXCEL\PLUTO\GPHSRTG.XLS!beta*((FU2_Mode2_Date-b6)/365.25)^2)
FU2_Mode6_Avail_Power	76.09	Watts	No_Fuel_Modules*Therm_Elect_Eff*BOM_Thermal*EXP(C:\EXCEL\PLUTO\GPHSRTG.XLS!alpha*((FU2_Mode6_Date-b6)/365.25)+C:\EXCEL\PLUTO\GPHSRTG.XLS!beta*((FU2_Mode6_Date-b6)/365.25)^2)
FU2_Mode7_Avail_Power	75.92	Watts	No_Fuel_Modules*Therm_Elect_Eff*BOM_Thermal*EXP(C:\EXCEL\PLUTO\GPHSRTG.XLS!alpha*((FU2_Mode7_Date-B6)/365.25)+C:\EXCEL\PLUTO\GPHSRTG.XLS!beta*((FU2_Mode7_Date-B6)/365.25)^2)
Flight Unit 1			
FU1_Mode1_Margin	18.24	Watts	FU1_Mode1_Avail_Power-PWRMODE.XLS!Mode1_Total_Power
FU1_Mode2_Margin	7.74	Watts	FU1_Mode2_Avail_Power-PWRMODE.XLS!Mode2_Total_Power
FU1_Mode6_Margin	8.69	Watts	FU1_Mode1_Avail_Power-PWRMODE.XLS!Mode6_Total_Power
FU1_Mode7_Margin	9.06	Watts	FU1_Mode1_Avail_Power-PWRMODE.XLS!Mode7_Total_Power
Flight Unit 2			
FU2_Mode1_Margin	18.97	Watts	FU2_Mode1_Avail_Power-PWRMODE.XLS!Mode1_Total_Power
FU2_Mode2_Margin	8.47	Watts	FU2_Mode2_Avail_Power-PWRMODE.XLS!Mode2_Total_Power
FU2_Mode6_Margin	9.42	Watts	FU2_Mode1_Avail_Power-PWRMODE.XLS!Mode6_Total_Power
FU2_Mode7_Margin	9.77	Watts	FU2_Mode1_Avail_Power-PWRMODE.XLS!Mode7_Total_Power

Calculation of BOM Thermal Power Using Equation (2)

Calculation of Flight Unit 1 Available Electrical Power for Critical Power Modes Using Equation (3)

Calculation of Flight Unit 2 Available Electrical Power for Critical Power Modes Using Equation (3)

Calculation of Flight Unite 1 and 2 Power Margins For Critical Power Modes Using Equation (4)

Figure 8—RTG Mass Computation

5 MODULE RTG MASS PROPERTIES				Variable Mass Fraction	Fixed Mass	Check
MASS (kg)	m.	Unit Mass	Total Mass	dMass/dFuel Module	Fraction	Sum
			15.36	2.294	3.90	15.36
Heat Source			7.24	1.*	0.00	7.24
Fuel (PuO2)	5	0.596	2.98	0.596	0.00	2.98
Capsules (Ir)	5	0.234	1.17	0234	0.00	117
Graphitics	5	0.618	3.09	0.618	0.00	3.09
Structural Supports			1.07	0000	1.07	1.07
Graphite Pressure Plates	2	0115	0.23	0.000	023	023
Load Studs & Zirconia	1	0.100	0.10	0.000	010	010
Belleville Spring (Ti)	1	0.370	0.37	0.000	037	037
Preload Hardware	1	0.370	0.37	0.000	037	037
Converter			2.15	0.430	0.00	2.15
T E Elements	160	0.009	1.51	0302	0.00	151
T E Fasteners & Seals	160	0.002	030	0.060	0.00	0.30
Alumina Insulators	160	0.002	024	004s	002	024
Connectors, Terminals	160	0.001	010	0020	0.00	010
MuM Foil Insulation			1.44	0.140	074	1.44
Sides	1	1.000	102	0.140	0.30	1.00
Ends	2	0.220	0.44	0.000	0.44	0.44
Support Structure	N/A	N/A	N/A	N/A		
Generator						
RTG Housing			2.90	0.1s7	1.91	2.90
Side Wall	1	1,410	1.41	0.197	0.42	141
End Covers, Bolts & Seals	2	0.302	0s0	Oooo	0.60	0s0
Pressure Release Device	1	0430	043	0.000	043	043
Resistance Thermometer	1	0.300	0.30	0000	0.30	0.30
Gas Mgmt. Assembly	1	01s0	0.18	000	016	0.16
Radiator Fins			0.ss	0.078	0.17	0.5s
Fins	1	0.510	0.51	0071	0.1s	0.51
Aux. Coolant Manifolds	N/A	N/A	N/A	N/A		
Emissivity Coating	1	0.050	0.05	0.007	0.02	0.05
Miscellaneous Elements	N/A	N/A	N/A	N/A		

adjust the number or size of other components and pads that make up the **RTG** subsystem. **Figure** 9 shows the cost computation for the RTG subsystem based on the WBS and the cost categories in Section 1.3. When a Pu238 brick is added, the cost is automatically recomputed by equations that adjust each **category**. For the RTG subsystem, this occurs in the flight hardware and **I&T** categories. In addition to these direct implications, adding an RTG brick initiates a series of ripple effects in other subsystems, which ultimately affects the **LCC** in ways that cannot always be anticipated, much less **superficially** calculated.

Some of the principal effects include an increase in propellant, **pressurant,** and tankage mass and spacecraft structure mass. Cruise time increases as a result of the increases in spacecraft wet mass, and MO&DA costs climb as **a** result. The direct gain in power margin during the Pluto encounter is slightly **offset** by the cruise time lengthening. The system/subsystem and project-level effects are summarized in Table 1. On the basis of the analysis, the addition of an RTG brick was rejected, and the original baseline was retained.

Table l-Effects of Adding One Pu238 Brick to PFF Spacecraft

SystemlSubsystem	**Projected Cost Effects**	**Projected Technical Performance Effects**
RTG	Higher	Higher subsystem dry mass, more **available** power
Power and Pyro	None	None
Propulsion	Higher	More propellant mass due to higher total (dry) mass, higher propellant tankage mass, more pressurant gas mass and gas tankage mass (partially **offset** by fewer ACS thruster firings)
Structure	Slightly higher	Higher mass and moments of inertia
Thermal Control	None	None
Spacecraft Data	None	None
Attitude and Articulation Control	None	Fewer thruster firings due to higher moments of inertial
Mission Design	**N/A**	Longer mission cruise time due to higher mass
MO&DA	Higher due to longer mission uise time	**N/A**
Project (Net Total)	**Higher**	**Higher** mass, significantly **higher** power margins, slightly lower expected science data return due to longer mission time

Lessons Learned

From these and other cases, we have compiled some lessons learned and observations about building the DTC model and about bringing DTC to a culture in **which** DTC is an unaccustomed feature. Some of these lessons learned and **observations** have implications for project managers as well as for system and subsystem design engineers.

When a project had already completed a substantial amount of conceptual and definition studies before a DTC model was initiated, the process of building the DTC model brought out the **project's** disconnects. These disconnects took several forms. For example, two different equipments **lists** were being used for mass and power consumption estimates. Different assumptions were being made about

Figure 8--RTG Subsystem Cost Calculation

Option 1 Description										
No of Flt Units = 3										
No. of Qual Units = 0										
No of GPHS/Unit = 6										
GPHS Source = Old Fuel (Mfg 7/1/83)										
WBS	**Description**	**FY[illegible]**	**[illegible]**	**[illegible]**	**FY97**	**[illegible]**	**[illegible]**	**[illegible]**	**Total ($FY93K)**	
E1000	**JPL Labor**	$0	$96	$315	$316	$321	$171	$0	$1,219	
E2000	**Procurement (NASA)**	$65	$130	$6,127	$8,650	$9,587	$1,297	$144	$26,000	
	Program Costs (Indep of production)	$30	$60	$2,828	$3,992	$4,425	$500	$67	$12,000	
	RTG Converters (3 FU's)	$15	$30	$1,414	$1,996	$2,212	$299	$33	$6,000	
	Qual Test & Refurbish to Flt Unit	$8	$15	$707	$998	$1,106	$150	$17	$3,000	
	F5 (Spare) Defuel + Handling	$12	$25	$1,178	$1,663	$1,844	$250	$28	$5,000	
E3000	**RTG Development (DoE)**	$100	$10,800	$14,000	$16,000	$11,000	$7,000	$300	$59,200	
E4000	**Radioisotope Fuel**	$0	$0	$0	$0	$0	$0	$0	$0	
		$165	$11,025	$20,442	$24,966	$20,906	$8,468	$444	$86,419	
WBS Number	**Description**	**FY94**	**FY95**	**FY96**	**FY97**	**FY98**	**FY99**	**FY00**	**Total ($FY93K)**	**Total Adj ($FY93K)**
	Radioisotope Thermal Generators	$165	$11,025	$20,442	$24,966	$20,906	$8,468	$444	$86,419	$86,419
	Design & Development	$130	$10,956	$17,143	$20,308	$15,746	$7,770	$367	$72,479	$72,479
	Flight Hardware (2 FU's)	$10	$20	$043	$1,331	$1,475	$200	$22	$4,000	$4,000
	Integration & Test	$25	$50	$2,357	$3,327	$3,687	$499	$55	$10,000	$10,000
	Flight SW	$0	$0	$0	$0	$0	$0	$0	$0	$0
					Standard Increment Delta (1 Fuel Module) =				0	

Total Adjusted Cost Depends on the Standard Increment Delta

11/16/94 10:16 AM

attitude knowtedge and control requirements by the AAC and propulsion subsystem design engineers. Different dates for key operations events were being used. The WBS contained flaws. We also found that hidden margins were being carried in subsystem designs simply because timely information about another subsystem's technical performance parameters were unavailable. These hidden margins added cost to the spacecraft's design and development.

When projects developed the DTC model from the start of conceptual studies, disconnects were either avoided or resolved much earlier. The DTC model fostered a clearer understanding of the mission across the project team. We found that the project team leader (usually the project system engineer) plays a crucial role in getting the project team to focus on the importance of costs from the beginning and to assign to each team member what "homework" needs to be done before each team meeting.

Developing a DTC model forced project teams to be more rigorous, timely, and forthcoming with data. Under the traditional design and development approach, subsystem design organizations tended to protect cost data and design margins as long as possible so as to avoid risk to themselves. Not surprisingly, this behavior lead to high cost, but was tolerated in "flagship" missions. In the DTC process, the DTC model is open to all on the project team and it makes the system-level implications of the design visible. This tends to lead to more questioning of assumptions and to earlier revelation of subsystem designs and costs. Project team meetings tend to be more interactive and involve more give-and-take (e.g., "Your subsystem's design causes me to do this, which adds x dollars. Can we find a way to avoid that?").

The other side of this information coin is that program/project managers have to *want to* know the kinds of data the DTC model produces. In order for DTC to work, managers have to demand that project teams report on the top-level metrics such mission effectiveness and life-cycle costs. Working against this is the observation that some managers view calculation of life-cycle cost as dangerous since it can be misused by others to endanger the project. Project managers also have to make it clear that the system and subsystem design engineers on the project team are accountable for the technical performance and cost equations and data they place in the DTC model.

Our DTC process requires some innovations in the way cost estimates are made. Project teams need to make grass roots estimates earlier in the project cycle. (To assist them, a data base of available hardware and planning tools are available in the JPL Project Design Center.) Project teams maybe asked to quantify the uncertainty in these grass roots estimates by providing probability density functions of costs. When new approaches or technology is involved, they also need to make estimates of the cost gradients with respect to subsystem technical performance. We have generally found that when a project's technical definition is weak, so are the cost estimates. The DTC model strengthens the earfy technical definition and performance requirements so that cost estimates can be made with greater confidence.

Lastly, we have found that education is needed not only in using the DTC model, but in the concepts behind it. The goal is for project teams themselves to be capable of quickly building a OTC model from an existing model for an already-completed mission. We anticipate that the library of completed models at JPL's Project Design Center will grow to a dozen or more over the next few years, and will include low-cost planetary flyby, orbiter, and lander missions, astrophysics observatory missions, and Earth-sensing missions. The number of studies that can be supported is currently limited by the number of Project Design Center personnel who have sufficient experience in building a DTC model. With previous models to serve as starting points and with project teams experienced in the process of building and using a OTC model, thus constraint will attenuate.

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